Progress Report on the Improved Linear Ion Trap Physics Package[1]

John D. Prestage, Robert L. Tjoelker, G. John Dick, and Lute Maleki

California Institute of Technology
Jet Propulsion Laboratory
4800 Oak Grove Drive
P - CA 91109

Abstract

This article describes the first operational results from the extended linear ion trap frequency standard now being developed at JPL. This new design separates the state selection/interrogation region from the more critical microwave resonance region where the multiplied local oscillator (LO) signal is compared to the stable atomic transition. Hg^+ ions have been trapped, shuttled back and forth between the resonance and state selection traps. In addition, microwave transitions between the Hg^+ clock levels have been driven in the resonance trap and detected in the state selection trap.

Introduction

Ions can be readily moved along the axis of a long linear trap [1] by applying a simple dc bias. This is a feature of ion trap based standards which has not been exploited. There are clear advantages for an Hg^+ trap layout where the ions are electrically moved from a state selection region into a compact microwave resonance region and then back for state interrogation.

In a frequency standard based on this concept [2,3], short and long term stability can be improved for several reasons. Magnetic perturbations and gradients caused by the optical state selection components, most notably the magnetic photomultipliers, can be eliminated since the optical and resonance regions are apart. Narrow resonances in the Hg^+ field sensitive transitions will enable measurement of the magnetic field in the resonance region and thus allow long term stabilization of this field. The volume of the region enclosed by the mag-

netic shields are reduced by a factor of 100 from that of the previous LIT design. For the present design the magnetic shields are 5 cm inside diameter by 37 cm so that multi-layering to achieve high shielding factors will not add much bulk or cost.
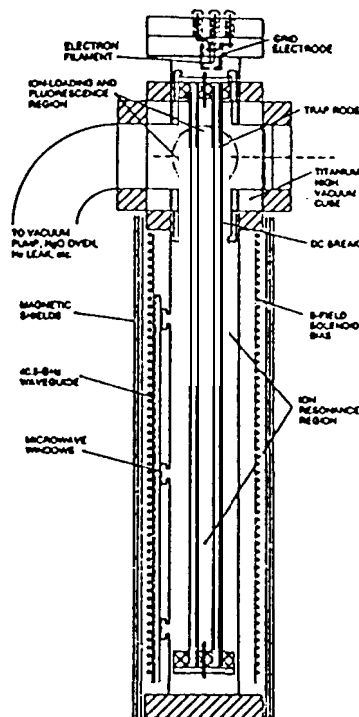
The 2nd order Doppler shift from the finite size cloud, proportional to the linear ion density N/L, can be reduced greatly by increasing the length, L, of the resonance trap. This frequency shift can be the source of clock instability if the number of trapped ions varies over time. The present trap, described in this paper, is about 4 times longer than the previous LIT design and should reduce number sensitivity by the same factor.

One of the limitations to short term stability in the present LIT standards [4] is the relaxation of the population difference between clock states during the microwave interrogation with the multiplied LO. This population difference is created by the optical state selection process which must be turned off during microwave interrogation because the UV light will shift and broaden the clock resonance and, therefore, degrade clock performance. The neutral Hg vapor which is necessary for ion creation will, over a period of ten seconds or so, replace (via charge transfer) a state selected ion with an ion in an arbitrary state of polarization. This degrades the resonance signal size, especially for the high Q measurements. One remedy for this is to remove the neutral Hg vapor from the resonance region by reducing the temperature of the vacuum walls in this region. Neutral Hg will be cryo-pumped (LN_2 temperature or higher) onto the walls and should lead to much improved signal size and clock performance. Because the optical and resonance regions are separated, the optical system and trap can be at room temperature.

Improved LIT Design

Figure 1 is a schematic view of the extended linear ion trap inside its vacuum container. A dc break forms a junction between the loadingktate-selection trap (upper) and the résonance trap (lower) and allows ions to be held in either trap region and to pass from one region to another. The rf trapping voltage for transverse containment of the ions is continuous across this de break. When the de voltage level of all four trap rods are the same m both the upper and lower regions thermal motion of the ions will carry them through the junction with no change m axial velocity. When the four trap rods in the upper region are at positive dc voltage with respect to the lower region trap rods, ions within a trap radius or so of the junction will be transported across the junction into the lower region. Only the ions near the junction will experience the electric field forcing them across the gap. Since each ion is in thermal motion along the axis of the trap it will reach the junction Within a trap length transit time (typically about 1 millisecond) and then be pulled into the upper region emptying the lower region of ions. Similarly, when the lower region is dc biased

positive with respect to the state selection region all ions will be transported from the resonance region to the state selection region. The helium buffer gas will provide the required energy damping with a 1/3 second time constant[5]. A ceramic ring at the junction of the two traps, supports on its inside diameter, the ends of each of the 8 rods from the two traps. The outside diameter of this same ring centers the trap inside the vacuum jacket. Similar rings are used at each end of the extended trap. These rings have a metallized coating to prevent charging and can be electrically biased from outside the vacuum. The ring at the trap junction, when biased to a few volts positive, acts as a partition between the two traps preventing ions from moving accross the junction.

Figure 2 shows one of the early measurements of ion fluorescence vs time as ions are shuttled back and forth between the two trap regions as just described. Ions only fluoresce when in the upper trap thus the fluorescence switches on and off corresponding to ion location. When the ions are in either trap, the partition electrode is biased to 10 volts or more with respect to the rf trap rods. The sequence of applied voltages used to move the ions from the state selection trap to the resonance trap follows: (1) the partition electrode is grounded; (2) a 1.5 volt dc bias on the 4 resonance trap rods is ramped to O volts in about 0.1 second; (3) the dc bias on the 4 state selection trap rods is ramped from O to 1.5 volts, and; (4) the partition electrode is again biased to 10 volts.

Following step (2) but before step (3) the ions move freely between the two traps as though it were one long trap. Following step (3) the ions are confined to the resonance trap. The partition serves to isolate the two traps so that the electron pulse can load more ions into the loading trap while the bulk of ions are confined to the resonance trap. This is done during the "fluorescence off" period of Fig. 2. The resonant 40.5 Ghz microwave pulse is continuously on during this measurement to prevent optical pumping and the consequent reduction of atomic fluorescence.

"Figure 1: Improved physics unit for the trapped ion frequency standard.[199]Hg ions are created and state prepared in the upper region of the trap, then transported into the lower region, where the Hg$^+$ atomic resonance frequency is compared with the local oscillator frequency. The ions are then moved back to the state selection region to check for frequency detuning from the LO during the resonance comparison. Overall dimensions are 10 cm by 50 cm.
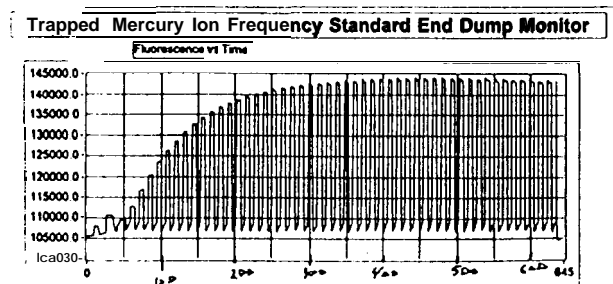

Figure 2: Ion population build-up while shuttling ions from resonance trap to state-selection trap and firing electron gun once per cycle to generate ions.
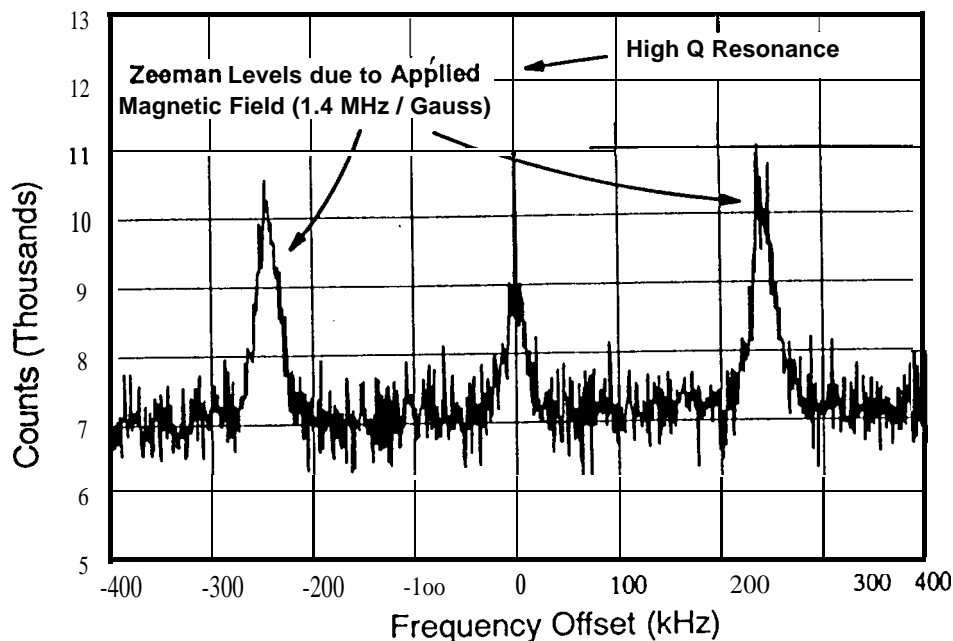
13 |

12 **Zeeman Levels due to Applied
Magnetic Field (1.4 MHz / Gauss)**

11

High Q Resonance

Counts (Thousands)

Frequency Offset (kHz)

-400   -300   -200   -1oo   0   100   200   300   400

Figure 4.   Title

Figure 4 shows the atomic resonance driven in the resonance trap and detected after the ions had been transported back into the loading/state-selection trap. To obtain this resonance curve, the "overshoot" fluorescence as seen in Fig. 3b is collected in a 2 second time interval which starts with the arrival of the ions back into the state-seleetion region. This fluorescence is measured as the, 40.5 Ghz source is swept in frequency by ± 400 khz around the $F=0, m_F=0$ to $F=1, m_F=0$ clock transition. The two field sensitive transitions $F=0$ to $F=1, m_F=\pm 1$ are spaced about 240 khz from the clock transition and correspond to a 170 mG magnetic field in the resonance trap. No attempt has been made to shim the field in the resonance region. These resonances are driven with high power microwaves derived from a Gunn oscillator locked to an H-maser reference source.

An improved architecture for a linear ion trap based frequency standard was built and ions have been trapped and moved back and forth between the state-selection and resonance trap with no loss of ions and with no relaxation of the atomic state preparation. Microwave resonances among the hyperfine levels have been driven in the remote interrogation region and detected in the optical state-selection region. Many of the design constraints of the present configuration are eliminated and a smaller, cheaper-nom stable frequency standard should result.

References

[1] J. D. Prestage, G. J. Dick, and L. Maleki, *New Ion Trap for Frequency Standard Applications*, J. Appl. Phys., vol. 66, pp. 1013-1017, 1989.

[2] J. D. Prestage, R. L. Tjoelker, G. J. Dick and L. Maleki, *Progress Report on the Improved Linear Ion Trap Physics Package,* Proc. 1994 IEEE Frequency Control Symposium, pp. 755-760,1994.

[3] J. D. Prestage, R. L. Tjoelker, G. J. Dick and L. Maleki, *Improved Linear Ion Trap Physics Package,* Proc. 1993 IEEE Frequency Control Symposium, pp. 144-147, 1994.

[4] R. L. Tjoelker, J. D. Prestage, G. J. Dick, and L. Maleki, *Recent Stability Comparisons with the JPL Linear Trapped Ion Frequency Standards,* Proc. 1994 IEEE Inter. Freq. Control Symposium, pp. 739-743, 1994.

[5] L. S. Cutler, R. P. Giffard, and M. D. McGuire, *Thermalization of* ^{199}Hg *Ion Macromotion by a Light Background Gas in an rf Quadrupole Trap,* Appl. Phys. B36, pp. 137-142,1985.